Advanced Hydrology
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Lecture – 36

Good morning, and welcome to this post graduate video course on Advanced Hydrology. Today we have reached the last module of this course, in which we will be looking at groundwater hydrology, as I mentioned in the last class. In the last class we completed the stochastic hydrology module, where in we had seen some numerical examples on the Gumbel's distribution, and the normal distribution and we looked at the hydrologic frequency analysis.

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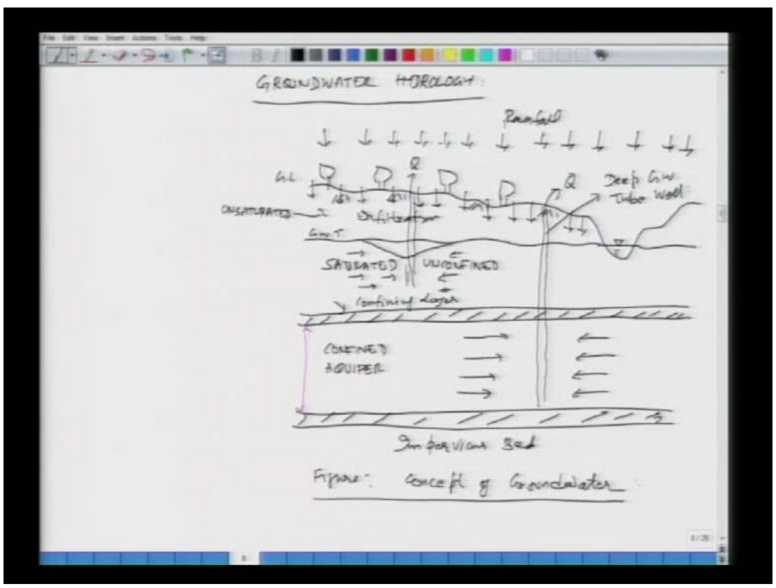

So, let us get started on this groundwater hydrology. First I would like to look at when the rain falls on a catchment or appears schematic like we normally look you know in a hydrologic cycle. So, let us see we have this ground, and there may be a river downstream somewhere, on the ground you will have lots of vegetation, so I am not drawing all of it, this is your ground level; we may have or the catchment, may experience certain amount of rainfall.

And we have seen in our earlier chapters, what happens to the rainfall is that, this rainfall actually goes through lots of storages in a catchment before it appears at the outlet in a river. And what are those different storages? Initially it gets intercepted in the interception storage zone, there may be some depression on the ground due to some puddles etcetera, and once those are satisfied, then we have the subsurface zone in which the water starts to infiltrate. So, if we go in here we have this water entering into the ground, which we call what infiltration, and actually we have seen infiltration in this course already, the Green-Ampt equations and so on, in the unsaturated zone.

Then we have a what is call, a water table, so this is the water surface elevation in the stream or in a river and this is what we call the groundwater table, this is called the unsaturated zone. So, if we look at a cross section of the earth just below the ground when the water infiltrates, this portion actually is called the unsaturated zone of the ground. And then we have the saturated or the confined aquifer, and we may have a confining layer somewhere down there.

So, this is some hard rock or some impervious layer or some confining layer, quite deep into the ground and this is what we call is the saturated zone , and this portion actually is what we call unconfined, we will come to these terms a little later. Unconfined is something which what we mean by that is which is not confined on the top, and then there may be another confining bad or rock strata or impervious bad, if we keep on going for the down, and let us say this is our another impervious bad,.

This is your confined aquifer, what is confined aquifer, a confined aquifer is one in which it is confined on either side, on top and bottom. Let us say we have dug a deep well, this is a well, and we take certain amount of water out, so what happens is water starts to travel towards the well. And then we need to be able to understand, how this water actually travels into a confining layer or in a confined aquifer, we may also tap into the shallow water resources that is into a unconfined aquifer, so this is your well.

And we may be discharging certain amount of water q from this unconfined aquifer, and as you know that the water table has a tendency to drop like this after we are discharging the water for a lot of time. So, again you have the water flowing towards this well from all the directions, when we are pumping the water out of this, this is what we call the deep groundwater well which is basically tapping the water resources into a very deep a confined aquifers. So, this is a figure basically we are showing the concept of groundwater.

So, we see that what happens to the rainfall when it enters into the ground as infiltration. We have an unsaturated zone in which the movement of water vertically downwards, we can model using Richard's equation we have seen many other equations already earlier. So, actually in this module we will mainly concentrate on the saturated portion of the ground water, unsaturated zone modeling we have done, we may look at a couple of equations which are applicable there.

So, what I would like to get started with this start looking at the what is the aquifer, how do we define an aquifer, there are different types water bearing formations of the geological formations, how does the water occur in the ground in the form of aquifers, and then what are the aquifer properties; so let us start looking at these things.

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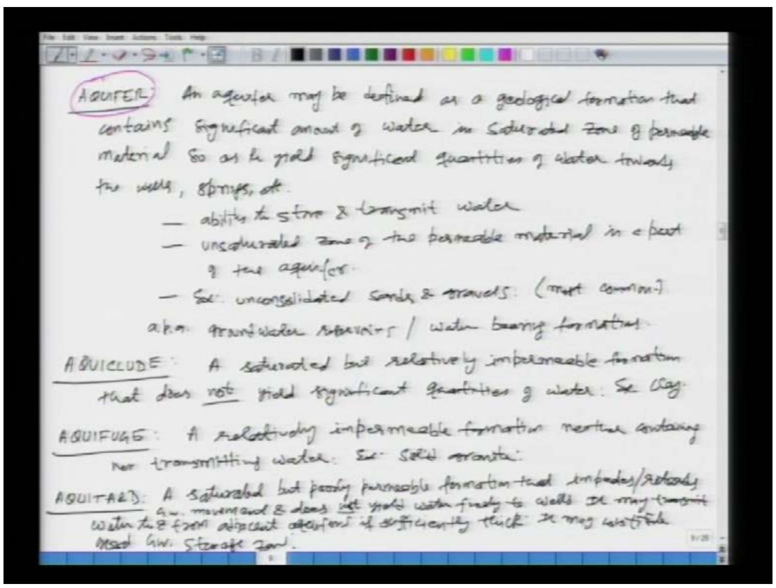

As we all know that water is stored in the underground what in what is called the aquifer, so how do we actually define an aquifer, an aquifer may be defined as a geological formation as a geological formation that contains significant amount of water, this is important, significant amount of water in the saturated zone of some permeable material. So, as to yield significant quantities of water towards the wells, and other natural phenomena such as springs etcetera.

So, what we are saying is that what is an aquifer; well it is a geological formation under the ground which can hold a lot of water, which can contain or store a significant quantities of water.

And then when we tap into it either through the well or it may be coming out as springs or you know some natural phenomena, we are able to get a significant yield or lot of water which we can withdraw, so it is not only able to store a lot of water, but it can transmit it also. So, aquifer has these two very important properties that it can store water, and it can transmit water also, so that we have significant yield for you know various purposes.

As we all know groundwater is very useful for the agricultural sector, and the drinking water supply, and many types of our water purposes. In fact, most of our agriculture other than the monsoon you know rains, it depends upon the groundwater, almost 70 percent of the sector. So, understanding the availability of groundwater in different types of formations or aquifers modeling it is movement, managing the water resources or optimally monitoring the wells and management of this water is extremely important.

So, this is an aquifer, we have just defined and as I said it has the ability to store and transmit, so these are two important words, the water another thing to remember or to note actually is that the unsaturated zone of the permeable material, is a part of the aquifer actually. So, what is an aquifer it is actually a geological formation, it may be unsaturated, it may be saturated, but as engineers we are always concerned about the saturated zone. Because, that is where the we get the water from, example of aquifers can be unconsolidated, sands and gravel different types of soils, will have different types of storage and transmissibility; and this these two are the most common actually.

Now, these aquifers are in fact, also known as groundwater reservoirs in certain books you will find different terminology, and all of these mean the same thing, groundwater reservoirs or water bearing formations; they are all one and the same things, however the word aquifer is the most common. So, let us move on and then we have another type of formation geological formation, it is called aquiclude, what is in aquiclude well, it is a saturated, but relatively impermeable, what is impermeable, impermeable is something which does not allow water to transmit or travel right.

So, it is a relatively impermeable formation or geological formation that is, that does not that does not yield significant quantities of water, and it is example is the clay strata or clay. So, we said that the aquifer is something, in which it has the ability to store water and transmit water such that, we can get significant yield from it, what is an aquiclude, aquiclude can actually store the water, but it is unable to transmit the water. Because, it has a poor permeability, due to the type of soil, you know clay or other kind of soil which have low permeability; so the yield cannot be significant it may be very small.

The next type of water bearing formation is what we call aquifuge, what is an aquifuge, it is a relatively impermeable formation, geological formation that is, neither containing nor transmitting water, and the example is some solid rock or solid granite formation. So, we see that we are moving in a direction where aquifer can give you significant amount of yield, then aquiclude s something which can give little amount of yield, and aquifuge is something which cannot even store water right; so it cannot it cannot store water and cannot transmit.

So, there is a there is hardly any water available in an geological formation which is called aquifuge, let us move on and then the next type of geological formation is called aquitard. I am sure you may have seen all these different terms, which are slightly different from each other, but none the less it is important to understand, what they represent. As the name suggests aquitard means it kind of retards the movement of water right, so it is a saturated, but poorly permeable poorly permeable formation that impedes or retards, so it is actually opposing the movement of water in fact.

So, we are going in a negative direction from aquifer to aquiclude to aquifuge and know aquitard, what the groundwater movement and does not yield does not yield water freely to wells. It may transmit this is important to note about this aquitard, it may transmit water to and from to and from adjacent aquifers, if it is sufficiently thick, it may constitute it may constitute good groundwater storage is on.

So, what is a aquitard then we are saying is that, it is a geological formation which impedes or retards the movement of water, so if you dig a well into an aquitard you will not be able to get actually any yield, because it does not allow the water to flow. But, the important thing is that an aquitard can transmit water or have interaction with other aquifers, so we may have an aquitard and below that there may be a confined aquifer or below or above that there may be a some unconfined aquifer, or it is adjacent to some other aquifer.

So, there may be some interaction of water taking place within the aquifers, or with the between two aquifers however, if you tap directly into an aquitard it is not able to transmit the water.

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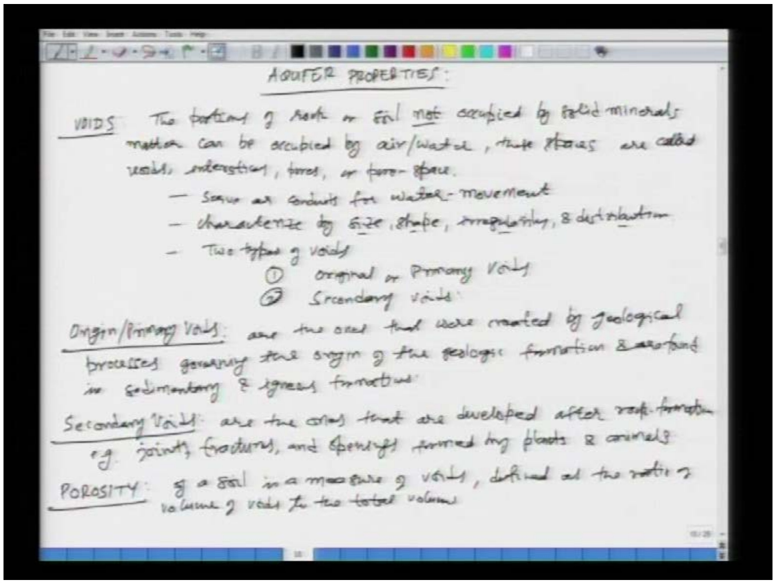

So, let us move on and look at what we call the aquifer properties, so what we have seen is basically the occurrence of groundwater in different types of formations, without going too much into the details. Now, it is important to understand different types of aquifer properties, after all all these different types of aquifers we have characterized, why are they different, because of the soil properties, and so on. So, these aquifer properties which depend upon the soil type, and the compaction and other conditions it is important to understand them, so that if we take the sample we can measure or estimate those quantities of the aquifer properties.

So, that we get some idea about the kind of aquifer it is which is there in a particular area, so that we can manage our water supply and you know a tapping yields and so on, accordingly. So, first we will look at the various types of these aquifer properties, you may have seen most of them or some of them at least, first one is the voids, I am sure all of you know what are the voids in a soil or in a aquifer, voids are some something which does not occupy the solid, soil, particles. So, it is you have a whole formation, whole volume and that whole volume you have certain soil solid particles, so this is that volume which is not occupied by the soil solids.

And the storage properties actually will depend upon this quantity of these voids, so understanding the voids and the void ratio etcetera all of these are important. So, if we write here the portions of a rock or soil, not occupied by solid minerals by solid minerals or solid particles a matter you can say, can be occupied by what by either the air or the water. These spaces in an aquifer are called voids, they are also known as in different books will follow different terminology, as I said interstices, interstices, interstices or pores or pore-space, they are all the same thing which is not occupied by the soil.

So, that this volume or this area is available for a air or water, now these voids are extremely important why because they serve as conduits, this is like your pipe network system in the underground. It serve as conduits for the water movement, that is where the water is actually moving in the in the ground; so understanding the kinds of voids it is very important. We characterize these voids, how by the size of these, we shape, a regularity or irregularity of your soil particles that is, and distribution etcetera.

So, we see that in different types of soil, you will have different types of you know sizes of the particles, the shapes may be different, the regularity or irregularities will be different, and how they are distributed over space will also matter. There are two types of voids, when we talk of you know ground water or the geological formations there are two types of voids, what are those first one is what we call original or primary voids. And the other one is what we call the secondary voids, some of you may not have seen these differences, so let us look at these very briefly.

What do we mean when we say the original or primary voids, as the name suggests, these are the ones that were created originally, after before a very long time, these were created by geological processes geological process is governing the origin of the geologic formation, and are found where in sedimentary and igneous type of rocks, sedimentary and igneous types of formations or rocks. So, this original or primary voids is a phenomena actually which is associated with the formation of the this geological formation itself. When the molten lava was cooling down, there will be some spaces in the rock seta or the soil seta which will be left out. So, we are referring to that when we are talking about the primary voids.

What are the secondary voids well, secondary voids are something which actually form after this original voids have been formed, so these are the ones that are developed that are developed after the rock formation, none the less these are natural these are not manmade we are talking. For example, there may be some joints which may develop, there may be fractures which may develop due to some you know activity, and the underground earthquake etcetera. And openings which are formed by the plants and animals, there may be there may be tiny insects or you know animals interfacing with the earth which may cause some very slight openings, so this is as far as the voids is concerned.

So, now let us look at some other properties and the first one of them we will look at is the porosity, so we looked at the voids and then we have defined what the voids are. Now, we want to quantify how much are the voids in a particular type of soil right, and there are different ways of doing that and porosity is actually one of them. We want to quantify that how much voids are there in that, if you take a 1 meter cube of sample of a particular soil, so what is porosity I am sure all of you know, of a soil is a measure of voids right.

That is what we just said, is defined as, defined as what the ratio of volume of voids, how much is the volume of the voids to the total volume. So, you take let us say unit sample, unit volume of a sample or a certain amount of you know sample volume, and you determine how much is the volume of the voids, and that ratio if you take the total volume and the volume of the voids that will give you the porosity.

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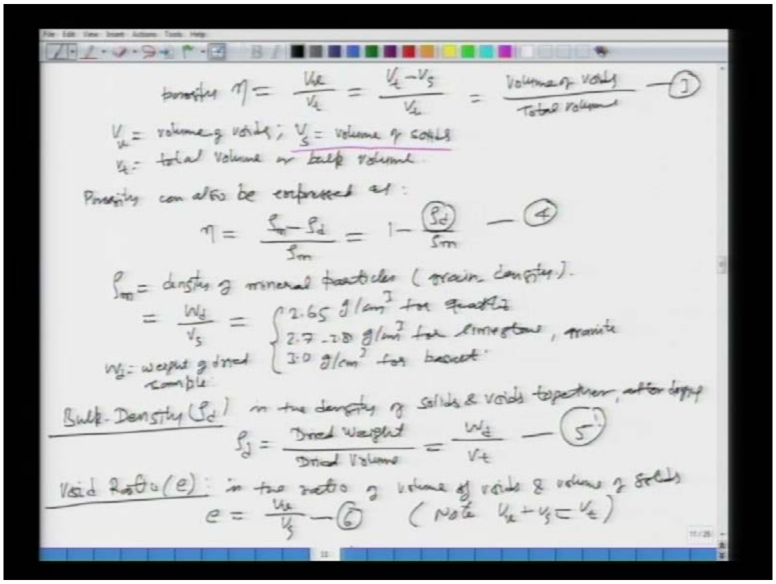

So, you define this porosity eta as V v power V t, and this also we can say as V t minus V s over V t, so basically what we are saying is that this is the volume of voids divided by total volume. Where what is V v, V v is the volume of the voids, V s is what as the name suggest it is the volume of the solids or the soil solids, and V t is the total volume or the bulk volume. Now, porosity can also be expressed in terms of densities, can also be expressed as the ratio of the densities or eta is equal to, you say rho m minus rho d over rho m which is nothing but a 1 minus of your rho d over rho m, let me number these equations, let us say this is 3 and this is 4.

What is rho m, rho m is actually defined as the density of the mineral particles, this is the density of the soil solids of the mineral particles or the solid rock, it is also known as the grain density, and originally of the kind of grains it is formed. this is given as the ratio of your W d over V s, and this is in the range of 2.65 grams per centimeter cubed for quarts, these are given in the book for different types of minerals, this is the grain density, this is 2.7 to 3.8 grams per centimeter cubed for the limestone, and granite granite, and other types of minerals.

And this is about 3.0 grams per centimeter cubed for basalt, what is W d I will define here, W d is the weight of your dried sample and V s we have already defined as this one here, volume of the solids. Now, this one quantity here rho d in the definition of your porosity here, what is the rho d it is called the bulk density, is the density of solids and voids together. So, this subscript here may be slightly confusing, but that is how it is defined that it is the density of the solids and voids taken together after drying, so there is no water in it. So, you take a sample you would completely dry it and you measure density that is called the bulk density, so we have rho d is what it is your dried weight, over the dried volume, total volume, so this is going to be your W d over V t, so let us say this is your equation number 5.

The next aquifer property or the soil property we will look at is what is called the void ratio, and this is denoted as e as you know what a void ratio is, it is the ratio of the volume of voids and the volume of solids. So, it is slightly different than what we have seen earlier as the porosity, so this e is actually then defined as volume of voids over volume of solids, this is your equation number 6. Now, please note that what will be the volume of voids plus volume of solids well that has to be equal to V t, we have been using this, equation without actually specifying it.

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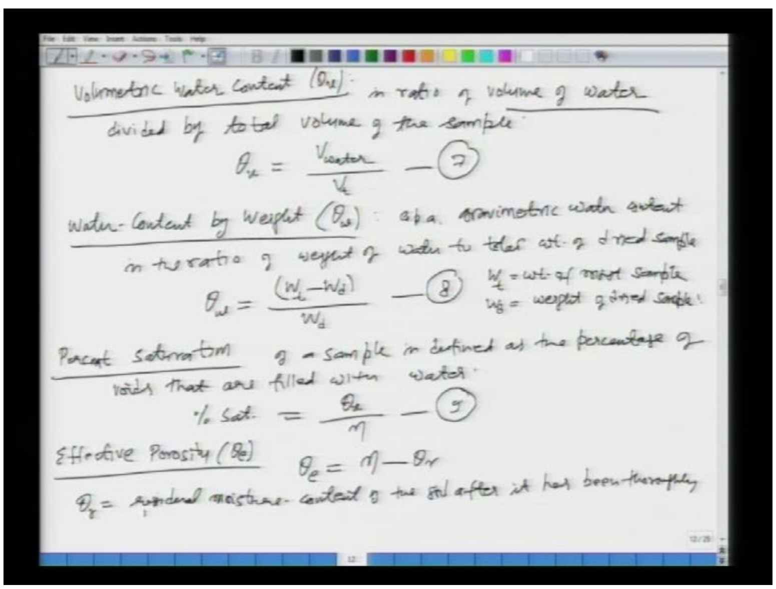

The next aquifer property we will define is what is called the volumetric water content, till now we have defined the a soil properties in which we are considering the soil solids or the voids, we have not talked about the water content right. Water content is extremely important in the saturated zone it will be 100 percent of course, but in the unsaturated zone lots of the soil properties will depend upon the a water content as we have seen, the section and the conductivity and so on.

The water content in the soil is defined in two different ways, you know those are few from the you know we are done a course on soil mechanics would know, that it can be expressed as a volumetric ratio or by volume, and it can also be expressed as by weight or which is called the gravimetric moisture content. So, let us look at both of these definitions quickly, is the ratio of volume of water, is the volume of water divided by divided by what the total volume of the sample, so this is represented as theta v as I said.

So, theta v is what it is the volume of water, it is not volume of voids, it is not volume of solids, it is not total volume, it is the volume of the water, which will be a fraction of the volume of the voids actually; so this is V t and this I say is equation number 7. Now, you define the water content by weight, and this is denoted as theta w right, it is also known as the gravimetric water content gravimetric water content is the ratio of what of the weight of water.

Obviously we are talking about the weight to what to the total weight of the dried sample, total weight of the dried sample here, not the moist sample the dried sample. So, the theta w then is equal to what is the weight of water well, it is the total weight you take initially minus the dried one, that is the weight of the water divided by the dried weight is this, so this is your equation number 8.

So, now we define it W t is the weight of the moist sample of the total weight basically, when you take the sample initially, and W d is the weight of the dried sample. So, we see we can carry out the experiments on a sample in a lab and calculate a many of these things, next property is what is called the percent saturation. And percent saturation of a sample or a soil sample is defined as what, as the percentage of voids percentage of voids that are filled with filled with water; so it is a fraction of a porosity or the total voids basically.

So, the percent saturation we say is what, the voids that are filled with water, what is the voids that are filled with water it is nothing but theta v, theta v is the ratio of the volume of water right. So, it is theta v divided by you say eta that is your percent saturation, which say that this is equation number 9. And the next property of soil is what is called effective porosity, we have seen this earlier actually when we were talking about the Green-Ampt equations etcetera in this course,.

So, what is the effective porosity it is basically the porosity, and then you subtract the water retention on in the soil or the residual moisture content after the soil has been thoroughly drained. So, there is some hydroscopic water which is held back by the soil solids, after the sample is allowed to drain completely under the influence of gravity. So, this effective porosity theta e is defined as the difference between eta and theta r, and let me just repeat or mention what is theta r, theta r is the residual moisture content residual moisture content of the soil after it has been thoroughly drained, it has been thoroughly drained.

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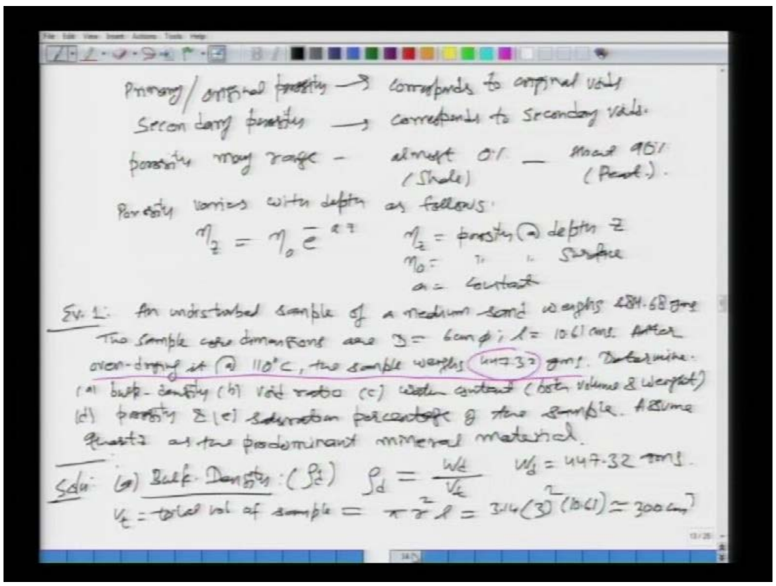

So, let us move on and quickly look at, we will just say that what is the primary and original porosity, we are looking at the porosity right, and the primary or the original porosity is the one which corresponds to obviously what, the original voids. We have defined what the original are and the secondary voids right, so this is the original voids, and then obviously the secondary porosity is what, something which corresponds to the secondary voids. Actually it is not easy to quantify this porosity into two different parts as we have said here.

But, for research purposes if we take the sample, if we look at the overall geological formation, the fractures and the joints play a very important role in the Karst hydrology, where water can move very quickly. So, sometimes it becomes necessary under certain kind of topography, and certain kind of geological formations to consider this secondary voids, if you take a sample, the soil sample from the aquifer and look at that porosity that will not explain the movement of water in a Karst type of hydrology, where there are lots of joints and fractures.

So, in certain cases it is important and necessary to actually quantify those things, but in normal circumstances we do not talk about this positional porosity or the secondary porosity. So, moving on this porosity actually may range, from where to where almost 0 percent which is for shale to about 90 percent for peat, 90 percent porosity is quite a lot actually, now there is a lot of people have tried to understand the porosity as a function of dept. As we go down into an aquifer what do you think will happen to the porosity, will it increase or decrease or will it get affected at.

Obviously, if you think little bit you should be able to see that as we go down into the ground, the porosity will actually change why, because of the degree of compaction as we go down the overburden increases and the compaction increases. So, actually you would think that the porosity would decrease as we go down, so people have carried out some research on that and we will just mention that the porosity varies with dept, as we go down as follows, that is your eta at any dept z is eta 0 times e to the power minus e z, where eta of your z is the porosity at dept z right, and eta 0 is what is the porosity at the surface, and a is a constant which we need to find for that particular area or a particular location. You see, so you see that the porosity actually exponentially decreases as we go down, because of the compaction, so when we are dealing with aquifers which are very deep. If we are dealing with the shallow aquifers, let us say you know 10, 20 you know meters, then it is may be not so important.

But, when we are dealing with deep aquifers or the deep confined aquifers of 100 meters, 200 meters, 300 meters, may be 1000 meters deep then this becomes extremely important that, you know we account for the variation of the porosity as a function of the dept. Otherwise, the result which we will obtain in terms of the groundwater movement, the yield out of that, all of that will not be correct or meaningful.

Now, what I would like to do next is, I would like to look at an example, a numerical example which will try to explain all of these different properties we have looked at see we have seen most of these properties you know which we may have seen earlier. So, we have porosity, we started with the voids, and then we define what is a porosity then we said what is the bulk density etcetera, the void ratio, then volumetric water content, the water content by weight or the gravimetric water content, percent saturation effective porosity and so on right.

So, what I would like to do is look at a numerical example in which we will take some data, and try to calculate some of these aquifer properties. So, here it goes an undisturbed sample of an undisturbed sample of a medium sand, weighs 484.68 grams, the sample core dimensions are given as follows that is your diameter of the core is 6 centimeter cylindrical, length of that cylinder is 10.61 centimeters. So, we see what is done is actually when we are doing these testing, you know we have this sample cores in which we take the sample out, and we or we dig it deep and take the sample in a particular type of shape of a core.

And normally these cores are cylindrical in shape, and the dimensions for this particular one are given, so we take the soil sample, so that we can calculate the volume of the total volume of your sample. So, that is what is given, then after what you do is after oven drying, so you take the weight of the sample which is given the oven drying will evaporate the water right, so that you will have the weight of the dried sample. After oven drying it at 110 degree centigrade, the sample weighs 400 and 47.32 grams, now determine, so these are the data given to us.

Determine a the bulk density, b the void ratio, c the water content by both volume and weight or gravimetric, t porosity and e a saturation percentage, the saturation percentage of the sample. And another important information that is given is that assume quartz as the predominant material for the aquifer, mineral material of your soils data. So, what I would like to do is quickly look at the solution in that order in which we have a defined these things, or which is being asked.

So, let us work on the bulk density, how is it representing rho of d and we have just seen what is rho of d, it is W d over V t is it not, it the data that are given to is what is W d, W d is what let me see the dry weight right, so after oven drying the sample weighs this much, this is your W d is it not, so that is your 447.32 grams right.

What is V t, V t is the total volume of the sample is it not and what would that be that would be this is cylinder or cylindrically shaped in a core, so it will be pi r square is the area at the bottom and the length is l. So, you have 3.14 or the diameter which is given is 6 centimeters, so the radius is 3 centimeter pi r square, then l is you 10.61 centimeters, so all of this will come out to be about 300 centimeters cube. So, it is actually 300 not 360, 300 centimeter cubed.

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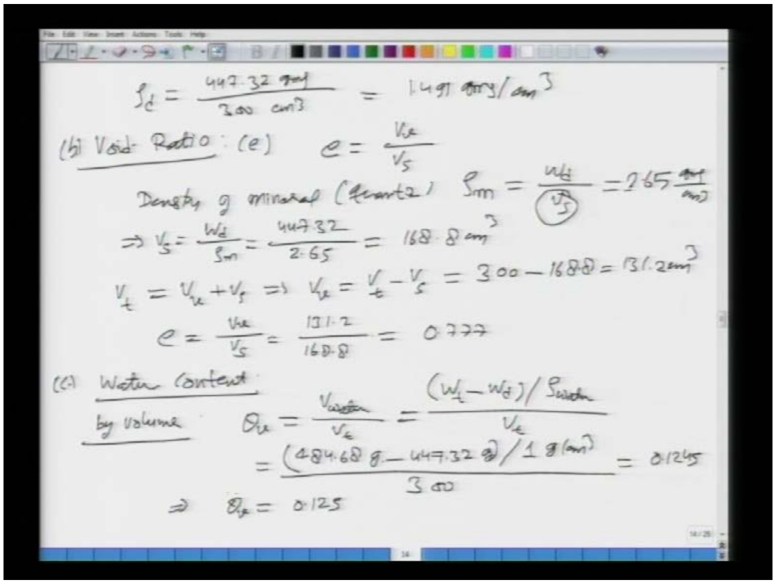

So, once we have these two things we can find out the bulk density rho d as 447.32 grams divided by 300 centimeter cube, so it will be 1.491 grams per centimeter cube is your bulk density. The second thing we have to find out is what is called the void ratio, which is e and it is given as V v over V s right, so we need to find out this V v and V s. So, let us see how we can do that the density of the mineral which is given to us as quarts that has V s embedded in it, so we use that definition rho m as your W d over V s that is the definition of you rho m, we have just said.

This is given to us as this is quarts, so for quarts we just take it from the standard table as 2.65 grams per centimeter cube, so you have the rho m as 2.65, you know what is W d? So you can find out V s from this. So, that means your V s or the volume of solids will be equal to what it will be W d over rho m, so it will be 447.32 divided by 2.65 is the rho m, so this will be equal to 100 and 68.8 centimeter of your cube. Now, we know that V t is equal to V v plus V s right, so from here we can find out what will be the volume of voids right, so it will be V t minus V s, and V t as we have found out is 300, V s is we just found out as 168.8 right, so it will be 130 1.2 of your centimeter cube right.

So, now we have both the things for finding out your e, so then e would be equal to sorry, V v over V s which is 131.2 divided by 168.8 both the units are centimeter cube, so it will be a fraction without units, so it will be 0.777 that is your answer. Now, let us look at the third part which is your water content, and water content first one we look by volume, this is theta b is defined as what the volume of water divided by the total volume. What is the volume of water well, it will be total weight minus the dried weight divided by the density of the water right, that will be the volume of water in the sample divided by V t of course.

So, this will give you theta v as W t is 484.68 that is the total weight of your sample that is given to us grams minus the dried weight was how much 447.32 grams, we divide this by what the density of water 1 gram per centimeter cube. This whole thing divided by V t and V t we have calculated as 300 centimeter cube, so this if you calculate it will be 0.1245, so you have theta v as 0.125 approximately.

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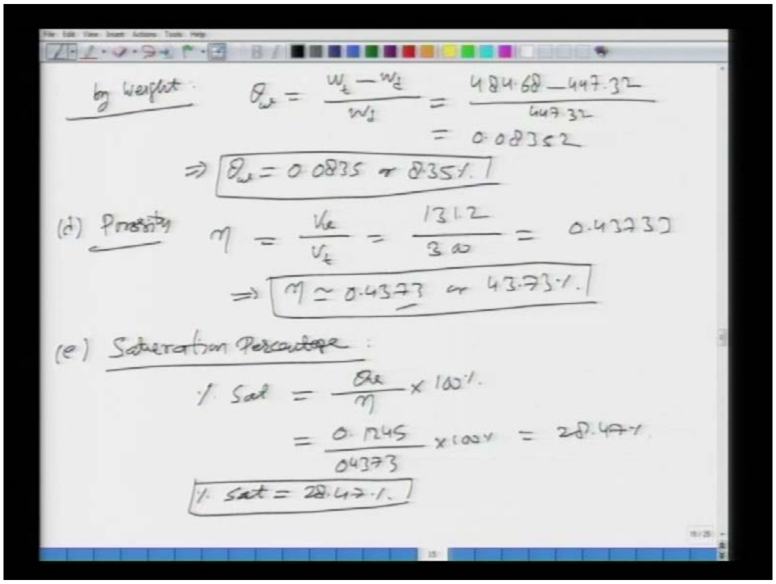

Water content by weight it is defined as theta as W t minus W d divided by what W d that is how it is defined, and all these things are actually known to us, so if you put the values it will be 484.68 minus 447.32 over 447.32 W d and W t, that will be approximately 0.08352. So, then you can say it is 0.0835 or 8.35 percent, that is the water content by weight, porosity eta is given as what volume of voids to volume or total volume, this is 131.2 we just found out and the total is 300, so it is 0.43733, so we say the porosity is 0.4373 or 43.73 percent.

The last thing we have to find here is what is called the saturation percentage, this saturation percent is given as theta v over eta. And if you want to express this as percent we multiplied by this, we have calculated both of these things theta v by volume, if we go back was how much 0.125, so this is 0.12, let me take the correct value 4 5 divided by 0.4373, this one we just found out, times 100 would be approximately 28.47 percent. So, the percent saturation of the sample is 28.47 percent.

So, this way we see that we have looked at all the different types of aquifer properties, and then we have seen a numerical example in which we take the sample from the field, we can bring that sample in the laboratory. And in the lab we can measure different quantities, we can measure the total weight, the dried weight and so on, and using very little amount of data you see that we are able to calculate different types of a soil properties. So, I think I would like to stop at this point of time today, and in the next lecture we will start with the movement of water or the Darcy's law, and you know other different types of equations.

Thank you.